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DESIGN PARAMETERS FOR STACK-MOUNTED LIGHT EXTINCTION MEASUREMENT DEVICES

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Abstract

The light attenuation characteristics of the smoke produced by fire are commonly measured in both fire experiments and standard fire tests. The results of these measurements are traditionally used for building and fire code regulatory purposes, design and testing of fire detectors, advanced material development, and life safety calculations. In addition, recent research suggests that for various fuels burning in over-ventilated fires, light extinction measurements may be used for the determination of the mass concentration of smoke per unit volume and smoke yield. The methods used for measuring light extinction in various fire tests and experiments are not consistent, however, and frequently do not take into account previously determined sources of uncertainty. This paper discusses existing methods of light extinction measurement, theoretical aspects of light extinction, and measurement device features that are necessary for the accurate and precise measurement of extinction. The topics are discussed in the context of smoke mass concentration and smoke yield determination for fire experiments conducted in the furniture calorimeter at the NIST Large Fire Research Facility and in other similar fire research facilities.

Design Parameters for Stack-Mounted Light Extinction Measurement Devices

A.D. Putorti Jr.

1.0 Introduction

The light attenuation characteristics of the smoke produced by fire are commonly measured in both fire experiments and standard fire tests. In order to understand and predict the hazards of fires to people, structures, or equipment, it is necessary to have the ability to measure the types and quantities of combustion products produced. The components produced, and their concentrations, are dependent on many factors, including the types of fuels, the mode of combustion, and ventilation conditions. While the by-products of combustion produced by fires consist of aerosols as well as gaseous species, for the purposes of this paper smoke is defined as the condensed phase products of combustion, such as particulate and suspended droplets of pyrolysate.

Measurements of light extinction have many uses, all of which attempt to use the amount of light transmitted through smoke as a representation of the concentration of the smoke. Until recently, the extinction measurements were correlated with other parameters such as visibility, fire detection, or irritation of mucosa. These relationships were historically developed for a generic "white"/"grey" smoke, or for "black" smoke in order to simplify their application to a variety of fuels and fires. The measurements were not used to gain an understanding of the actual makeup of the smoke in terms of particle size distribution or chemical composition.

Theoretically, the magnitude of light attenuation relates to the mass concentration of smoke via the specific extinction coefficient, which embodies basic smoke properties such as particle size distribution and optical properties of the particles. Recent research[1] suggests, however, that for over-ventilated fires, the specific extinction coefficient is constant for the smokes from a variety of different fuels. This relationship makes possible the calculation of the mass concentration of smoke from a measurement of light extinction.

The purpose of this work is to investigate functional characteristics for a device that could be used to make light extinction measurements with application to the determination of smoke mass concentration and soot yield from burning materials. While the correlations developed for white and black smoke have proved useful in the past, the methods used for measuring light extinction in various fire tests and experiments are not consistent, and frequently do not take into account previously determined sources of uncertainty. The measurements can be made in a manner that allows the application of hazard correlations from previous research, yet provide data that can be related to particle mass concentration using light scattering theory. The works of various investigators can be compared more easily if the measurement device is standardized.

Measurements of light extinction with a standardized device would allow for a greater understanding of the effects of smoke on visibility, fire detection, irritation, and property damage by better characterization of smoke. Parallel works by other investigators aim to determine the specific extinction coefficients used to derive the smoke mass concentration and smoke yield from the light extinction measurement.

This study has been conducted to identify the characteristics of a light extinction device, based on sound technical principles, incorporating modern components, of moderate cost, possessing good accuracy and precision, and the ability to operate in dirty environments with little maintenance, are developed. Commercial products designed to measure light extinction in stacks for pollution monitoring may be appropriate for measuring light extinction in the instrumented exhaust hoods of the NIST Large Fire Research Facility and in other similar fire research facilities.

2.0 Background

2.1 Smoke Produced by Fires

The quantity and characteristics of the smoke produced by fire is dependent on many factors, not all of which are characterized to allow prediction of smoke properties from first principles. The mode of combustion, flaming or smoldering, has a large effect on smoke properties. The smoke from smoldering combustion tends to be made up of smoke droplets consisting of partially oxidized products that have condensed forming an aerosol. Unburned pyrolysis products form a similar type of smoke. The smokes formed from smoldering combustion and those containing a high percentage of unburned pyrolysis products tend to be light or grey in color. In contrast, the smokes formed from the flaming combustion of materials tend to be dark in color or black. A large proportion of the smoke from flaming combustion consists of elemental/graphitic carbon.

The smoke from combustion occurring in the confines of a structure or limited volume will be affected by the ventilation conditions. Ventilation limited fires would be expected to produce a number of partially burned pyrolysis products, resulting in smokes with various proportions of carbonaceous and condensed droplet constituents. The chemical makeup and orientation of the fuels and fuel packages will also effect the amount and composition of the smoke produced. Currently there is no data on the specific extinction coefficients of such smokes from the burning of realistic materials.

The characteristics of the smoke produced will be affected by aging. After the smoke has exited the combustion site, condensation may form more smoke droplets, smoke particles may agglomerate into larger particles, particles may fall out of the smoke, and particles may stick to surfaces. Flaming combustion produces complex agglomerate structures, consisting of a large number of spherules. The size of the agglomerate structure is on the order of micrometers, while the individual spherules are on the order of 0.030 μm to 0.050 μm in size.[2]

2.2 Effects of Smoke on People and Property

Due to the focus of this work on the light extinction properties of the smoke, this section will ignore the temperature effects of smoke and the potentially toxic effects of combustion gases such as CO, NO_x, HCN, HCL, etc. The presence of smoke aerosol resulting from fires, however, is important for life safety and property protection. Smoke produced by fires will travel into egress paths, limiting visibility, and possibly causing irritation of the mucosa of exiting occupants. The limited visibility and irritation will serve to delay or prevent the timely egress of occupants. Property damage may occur from the presence of smoke. Smoke deposits may cause discoloration and staining, produce difficult to remove odors on products and furnishings, and etch or corrode equipment. Some types of equipment, such as electronics, are especially susceptible to smoke aerosols.

Previous research investigated the effects of smoke concentration on visibility and on egress. Visibility can be quantified by determining the visible range, which is defined as the distance at which a test object is just distinguishable from background. The color of smoke was found to have an effect on the visible range, as does the irritation caused by some smokes.[3] The visibility of exit signs in "black" smoke was found to be better than in "white" smoke, and exit signs were less legible in irritant smoke versus non-irritant smoke. It is important to note that the visibility is not a simple function of smoke density, but is rather a function of the contrast between an object and its surroundings. The visible range for white smokes, which absorb less and scatter more light, is less than for black smokes. Nevertheless, approximate relationships were found between extinction coefficients for black and white smokes and visible range. In timed egress calculations, a design maximum limit is set for smoke density that will allow for safe egress.

2.3 Uses for Smoke Measurement.

The quantity and concentration of smoke produced by fire are of interest for several different purposes. Measurements of the light extinction characteristics of the smoke allow for calculations of visible range, and could be used to provide an indication as to the level of irritation that may result from exposure. These analyses could be used for predictions of conditions hazardous to life for purposes of design, egress, or forensics. Historically, the choice of wavelength for the measurement of light extinction for applications related to vision was white light. The detectors used in these devices were typically chosen to simulate the spectral characteristics of the human eye.[4]

Extinction measurements may be used to calculate the mass density of smoke particles per unit volume, and the mass of smoke produced per unit mass of fuel burned. If the smoke is successfully characterized, the results could be useful in predicting the response of ionization and photoelectric type smoke detectors. Extinction measurement devices are currently in widespread use in various industries for the monitoring of stack and vehicle emissions.

2.4 Standard Test Methods Incorporating Light Extinction

There are many standard fire test methods that make use of light extinction measurements, ranging from small scale tests to large scale tests. The primary purpose of some test methods is to measure the amount of the smoke produced by materials undergoing combustion, while others incorporate smoke measurements as a secondary measurement. Several tests were developed in response to high fatality fires, where materials used in construction were thought to produce excessive quantities of smoke while burning. These tests are in use by regulatory authorities to limit the smoke production propensity of materials used in buildings. Some of the small scale tests are used for the development of materials with lower smoke production.

A third category of tests incorporate light extinction measurements as a way to provide consistent smoke conditions while a test is conducted, such as a test to gauge the response of a smoke detector. Specific test methods are discussed in detail in section 4.0.

3.0 Theory

3.1 Light Extinction due to Particles

The intensity of light passing through smoke will be attenuated due to interactions with suspended particles. The particles will scatter and absorb light. The attenuation of light passing through an aerosol medium such as smoke was described by Bouguer[5], and the following is known as Bouguer's law or the Lambert-Beer law[6]:

$$I = I_0 \exp(-K_{ex} L) \tag{1}$$

where: $I \equiv$ transmitted light intensity
$I_0 \equiv$ incident light intensity
$K_{ex} \equiv$ extinction coefficient
$L \equiv$ light path length

In addition:

$$K_{ex} = K_m m \tag{2}$$

where: $K_m \equiv$ extinction coefficient per unit mass = specific extinction coefficient
$m \equiv$ mass concentration of smoke aerosol

The specific extinction coefficient is determined by the size distribution and the optical

properties of the smoke. Bouguer's law is valid for monochromatic light and for a detection system collecting only transmitted light. In reality, there will always be some forward scattered light collected in addition to the transmitted light. For small particle sizes, the light is scattered relatively uniformly in every direction so that light scattered in the forward direction is a small fraction of the total. As the particle size increases the scattering intensity becomes more intense in the forward direction. The scattering effect is less significant for flame generated smoke, since 70% or more of the light extinction is a result of light absorption.

Multiple scattering can be a problem at high particle concentrations for detectors with large acceptance angles. As the particle concentration increases, the angular distribution will be less forward directed. By designing a system with a small acceptance angle, the effects of both forward and multiple scattering are minimized.

3.2 Smoke Particle Attributes

As discussed in earlier sections, smoke aerosols from smoldering fires are composed mostly of condensed pyrolysate and partially oxidized fuel. The smoke aerosol size is often expressed as a volume-to-surface mean particle diameter. Research has indicated that for treatments of Bouguer's law for polydisperse aerosols, that the extinction coefficient is a function of the mean volume-to-surface particle diameter, and not sensitive to the actual size distribution of the smoke.[7] This may be the result of the observation that the size ranges of smoke particles approximate log-normal distributions. The volume-to-surface mean particle diameter ranges in size from approximately 0.75 μm to 0.8 μm for the pyrolysate from Douglas Fir, to approximately 1.4 microns for smoldering cellulosic insulation.[2] For use in standard treatments of Bouguer's law, the mass median particle diameters for smoldering smoke near its source were found to be approximately 2 microns to 3 microns.[6] Since the aerosols are composed of droplets roughly spherical in shape, a variety of size measurement methods result in similar diameters.

The smoke from flaming combustion is composed mainly of elemental or graphitic carbon. Existing particle size measurement methods, while satisfactory for the spherical particles from pyrolysis and smoldering combustion, do not adequately quantify the attributes of agglomerates from flaming combustion. These agglomerate structures are composed of 10 to 10^6 primary sphereles, with a total agglomerate size ranging from 0.1 micrometer to 10 micrometers.[8] The spherules that make up the smoke particles have diameters on the order of 0.03 microns in diameter.[2] Aged smoke would be expected to contain larger particles.

3.3 Parallel Research

An on-going study at NIST is concerned with the measurement of light extinction and smoke mass concentration in highly controlled, small-scale experiments. The specific extinction coefficients were measured for various fuels undergoing flaming combustion under over-ventilated conditions. The study[1] has resulted in suggested values for the specific extinction coefficients of various fuels, and a single value for use with a range of fuels burning under over-

ventilated conditions. These results were in agreement with extinction coefficient measurement results from other investigators. The fuels ranged from gaseous and liquid hydrocarbons to common materials found in building materials and furnishings. The recommended value for the specific extinction coefficient is 8.5±2.0 m^2/g for a helium-neon laser light source with a wavelength of 632.8 nm. The uncertainty band takes into account the effects of fuel type, the scale of the fire, and combustion conditions such as radiant fluxes and flow rates. For white light sources, and a CIE 1924 Photopic filter before the detector in the measurement apparatus, the recommended value for the specific extinction coefficient is 9.6±3.0 m^2/g. The uncertainty band takes into account additional variables including the spectral properties of the light source, the CIE 1924 filter, and the detector.

In order to use the recommended values for the specific extinction in a wide variety of light extinction meter designs which may incorporate light sources of various wavelengths, the following expression may be used[1]:

$$K_m(\lambda) = \frac{632.8}{\lambda} 8.5,\ m^2/g \qquad \textbf{(3)}$$

where: $K_m \equiv$ specific extinction coefficient
$\lambda \equiv$ wavelength of light, nm

For light sources producing a range of wavelengths, the attenuation would need to be integrated over the wavelength range.

It is interesting to note that the fuels that agreed well with the use of a common value for the extinction coefficient were fuels that produced smoke consisting mostly of carbonaceous materials. In contrast, materials tested that contained silicon, produced silica aerosols. These smokes had specific extinction coefficients in the range of 1.7 m^2/g to 3.0 m^2/g, which is a factor of 3 to 5 less than the recommended value. For smoldering smoke, Seader and Einhorn[9] found specific extinction coefficients of approximately 4.4 m^2/g for materials such as ABS, polystyrene, urethane, alpha cellulose, and Douglas Fir.

3.4 Design Concepts

In order to make extinction measurements that satisfy the assumptions in Bouguer's law, and provide specific extinction coefficients that are independent of mass concentration, a properly designed apparatus is necessary. Works by Cashdollar[7], Deepak and Box[10, 11], Hodkinson[12], and Mulholland[6] are excellent references for these measurement device characteristics.

Due to the dependence of the specific extinction coefficient on wavelength, the measurement device should ideally operate with a monochromatic light source. The sample beam width

should also be small in relation to the length of the beam, in order to avoid perspective effects within the measurement volume. For designs incorporating collimator lenses, forward scattered light can be avoided by the incorporation of an aperture, as shown in Figure 1. Deepak and Box provide estimates of error which may be used as a criterion for the design of apertures. The true intensity ratio is related to the intensity ratio measured with an extinction instrument as follows:

$$\frac{I}{I_0}=\left(\frac{I_m}{I_0}\right)^{\frac{1}{R}} \tag{4}$$

where: I_m=measured transmitted light intensity
R=intensity ratio correction factor

The value of R is derived from a graph where R is plotted as a function of a nondimensional parameter y, defined as follows:

$$y=\frac{\pi d}{\lambda}\theta_1 \tag{5}$$

where: d=particle diameter
λ ≡ wavelength of light
θ_1 ≡ angle subtended by the diameter of the aperture at its lens (radians)

Since the severity of the criterion increases as particle size increases, the largest smoke particles anticipated should be considered. A reasonable upper limit on smoke particle size from full scale compartment fires is approximately 5 µm in diameter, considering scale effects and coagulation.[6] Given a wavelength of 0.550 µm, particle diameter of 5 µm, and an angle of 2 degrees, the value of R is approximately 0.9.

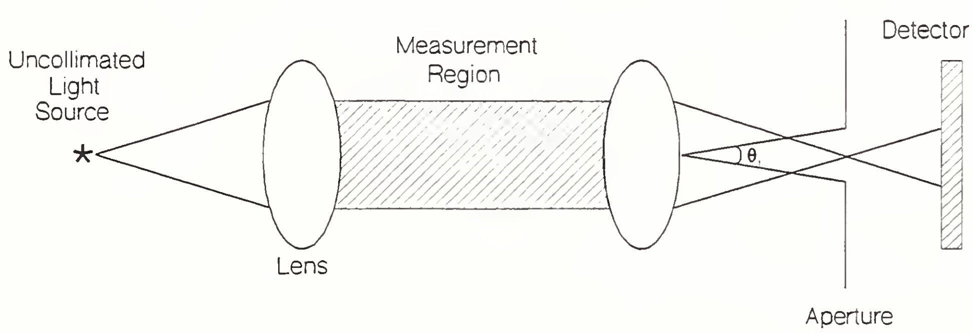

Figure 1. Smoke meter using uncollimated light source.

These criteria are approximations since smoke particles from flaming fires are not spherical. In practice, however, excellent results were obtained by limiting the angle θ_1 to 2 degrees. This rule of thumb considers the non-spherical structure of the smoke agglomerates produced by flaming fires. Details of the scattering and absorption by agglomerates can be found in the literature.[13]

For extinction devices utilizing coherent light sources, an arrangement such as is shown in Figure 2 can be used to prevent forward scatter. The angle θ_2 should be less than 2 degrees in order to minimize the measurement of forward scatter for typical carbonaceous smoke particles.[14]

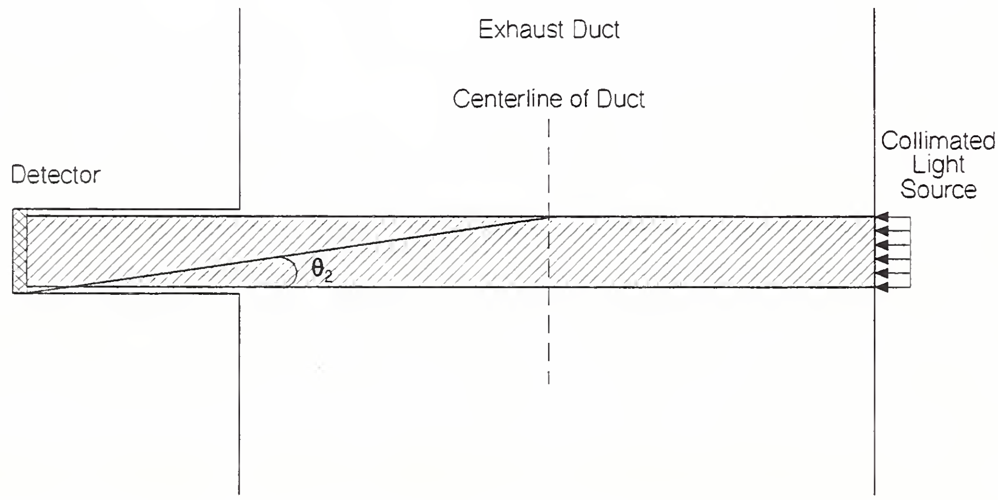

Figure 2. Smoke meter using collimated light source.

If the particle size distribution of the smoke is known, corrections may be made to extinction measurements to account for forward scattered light.[11] Given the application of the extinction measurement device in this paper to generalized smokes from flaming combustion, the use of these corrections would significantly reduce the utility of the approach. Instead, the design philosophy is to reduce the effects of forward scattering to levels consistent with the levels of uncertainty of other measurements needed for the smoke concentration determination, and accomplish this by careful design of the light extinction measurement device. Note that the errors for black smokes are on the order of half or less than those from white smoke because a large fraction of the light is absorbed by black smoke.[15]

3.5 Smoke Yield

The common method for expressing the quantity of smoke produced by a fire is to calculate the ratio of the mass of smoke produced versus the mass of fuel burned. This non-dimensional quantity is calculated as follows for a fire burning under an exhaust hood:

$$\epsilon = \frac{m_{smoke}}{m_{fuel}} = \frac{K_{ex}(T_1)\ \dot{m}(T_1)}{K_m\ \rho(T_1)\ \dot{m}_f} \tag{6}$$

where: K_{ex} ≡extinction coefficient. Calculated from extinction measurements, (I/I_0), and Bouguer's law. See section 3.1

$\dot{m}(T_1)$ ≡hood mass flow rate. Calculated from pitot tube and temperature measurements.

K_m ≡specific extinction coefficient. Determined in the laboratory under highly controlled conditions.

L ≡path length. Required for calculation of K_{ex}. Determined from the construction of the extinction device. Includes corrections for the use of purge air and boundary layers in the duct.

$\rho(T_1)$ ≡density of exhaust at T_1.

$\dot{m}_f$ ≡fuel mass loss rate. Measured with a load cell during the fire experiment.

T_1 ≡temperature of stack gases at extinction measuring location.

ϵ ≡mass of smoke produced per unit mass of fuel burned (smoke yield)

The smoke yield of the fire is the final quantity calculated from the measurements obtained by the smoke extinction meter and other instruments.

4.0 Existing Light Extinction Measurement Systems

4.1 Published Systems Accepted by Standards Organizations

Various standard fire test methods consist of, or include measurements of light extinction. The following list contains a brief description of several tests and the operational characteristics of the device that measures the light extinction. The devices differ in design and operation, goal of the measurement, type of light used, application of the test results, caveats, and benefits. Each of

the devices contains particular design features or deficiencies that make the measurement better or worse according to theoretical aspects discussed earlier. Smoke flow through designs are constructed in a manner that allows the smoke generated to pass through the light extinction area and out of the apparatus. Non flow through designs contain the smoke that is generated and measured.

ASTM E 84 - 91 "Standard Test Method for Surface Burning Characteristics of Building Materials."[16]
This test method is also known as the Steiner Tunnel test, and is used for determination of horizontal flame spread. The test apparatus is a flow through design. A photometer system for measurement of smoke density consists of a photocell and a 12 V, sealed beam, clear lens, automotive spot lamp. The path length between the light source and detector is approximately 914 mm (36 in.). The openings provided for light passage through the apparatus are approximately 76 mm (3 in.) in diameter. No apertures are present to restrict forward scattered light.

ASTM E 662 - 93 "Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials."[17]
This test method is also known as the NBS Smoke Chamber test, and is used to determine the quantity of smoke produced by a small sample of material. The test apparatus is a non flow through design, in which all of the smoke produced is collected. The photometric system consists of an incandescent light source with a photomultiplier tube for detection. The color temperature of the light source is specified in order to standardize the emission spectrum of the source. Optics are included for collimating of the light beam. The light beam diameter is approximately 38 mm (1.5 in.). An aperture is present.

ASTM E 906 - 83 "Standard Test Method for Heat and Visible Smoke Release for Materials and Products."[18]
The test method measures the heat and smoke evolved from the combustion of a small, irradiated sample. The test apparatus is a smoke flow through design. A smoke monitor measures the light extinction of smoke leaving the apparatus, and consists of a miniature incandescent lamp and photocell. The light is not collimated, and no aperture is present to prevent forward scattered light from being measured.

ASTM E 1354 - 92 "Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter."[19]
This test method is also known as the cone calorimeter test, in which a small-scale sample is burned while being irradiated. The smoke measuring system consists of a He-Ne laser with a wavelength of approximately 632.8 nanometers and a silicon photodiode detector. The light beam is split prior to the measurement volume, with a reference detector present to monitor the light source during smoke measurements. An aperture for reduction of forward scatter is not present, but light paths are limited by a nominal 8 mm (0.3 in.) tube which excludes forward scattered light.

UL 217 "Single and Multiple Station Smoke Alarms."[20]
This standard establishes requirements for the smoke detector/notification units found in single family homes. The standard contains requirements for a sensitivity test for the detector's response to various types of flaming and smoldering smokes, which are conducted in a test chamber. The extinction measurement system is very simple, and the specification of its characteristics is vague. It consists of an automotive tungsten filament lamp and a photoelectric cell spaced approximately 1.5 m (18 in.) apart.

4.2 Commercial Systems

Commercial systems specifically designed for the measurement of light extinction in fire experiments are very limited. These systems are nearly identical to those present in one of the standard tests discussed in Section 4.1. Of these systems, only that from ASTM E1354 appears to incorporate features necessary to satisfy the assumptions of Bouguer's law. This is known to be in use by several laboratories and universities for measurements of smoke density from full-scale fire experiments.

Although not specifically designed to measure light extinction for the calculation of the mass concentration of smoke, there are many devices commercially available for monitoring the opacity of effluents discharges from industrial stacks. These devices are specifically designed to meet US Environmental Protection Agency (EPA) requirements.[21, 22] Designs are available that measure the attenuation of light by smoke within stacks. In order to lower the initial and maintenance costs, some of these devices incorporate a double pass design, where a retro-reflector at one side of the stack returns the attenuated light beam to the device. These types of devices may not be compatible with precision smoke measurements due to the possibility of measuring forward and back-scattered components.

Single-pass devices for stack measurements are also available. Unfortunately, current EPA regulations do not allow the use of laser light sources, so the manufacturers utilize either light emitting diodes or tungsten light sources. Collimating lenses are therefore necessary, and some manufacturers incorporate apertures. In addition, filters are used in the devices with tungsten light sources in order to limit the wavelength band that reaches the detector. One particular device incorporates the necessary features from section 4.1, however the aperture size must be checked and perhaps modified. In addition, a filter with a smaller wavelength band must be incorporated in order to reduce the quantity of polychromatic light reaching the detector. The measurement device also includes a reference beam and comparator circuit, which results in a ratio between the reference beam intensity and the transmitted intensity and corrects for long and short term changes in the light intensity provided by the lamp.

4.3 Applied Systems, Measurements, and Results

The results of extinction measurements from full scale experiments are difficult to compare due

to differences in the measurement methods used by various investigators. The measurement techniques are not standardized and frequently are conducted without considering common sources of significant errors. In addition, light extinction measurements are frequently not fully documented, making duplication by other investigators impossible. Measurement methods range from the use of automotive headlights and photo-detectors without apertures to He-Ne laser beams and small aperture collection optics, with some systems based on those present in the ASTM standards listed in section 4.1. Measures of uncertainty are often not provided, resulting in unknown levels of accuracy and precision.

An interesting series of experiments was conducted comparing obscuration measurements in the cone calorimeter using the standard He-Ne laser system (monochromatic) and a white light system with a response meant to simulate the optical response of the human eye.[23, 24] Materials burned included polyurethane foam, particle board, and gypsum board. The study found that both systems gave equal results, although levels of uncertainty are not stated. The reason for the agreement is not known since the recommended specific extinction coefficients for He-Ne and white light sources are different (see section 3.3). Due to the results of the study, however, various sets of room fire experiments were conducted using the white light system.[25] Past studies have demonstrated that significant errors may result from the use of white light systems.[4]

5.0 Currently Available Components

Improvements in the various components used in the construction of a light extinction device are constantly occurring due to the use of the components in communications and medical applications. Device characteristics of most interest to this work relate to reduced costs, improvements in the ease of construction and in maintenance of the extinction device, and light source choices (wavelength, etc). Absolute performance of the components is of less interest due to the relatively undemanding application to light extinction as compared to gaseous species absorption, scattering, or spectroscopy. An exception to this generalization would be the use of sophisticated electronics to avoid expensive light source power supplies for stability.

5.1 Light Sources

In order to improve the ease of use, adjustment, and maintenance of the smoke measurement device, it would be beneficial for the light source to be within the visible range. Ideally, the wavelength of the source would be near the center of the visible range to allow straightforward comparison with previous research using white light and detectors with responses similar to the human eye. However, the primary purpose of the device is to calculate the mass concentration, and any narrow wavelength band (filters may be necessary for broadband sources) within the visible range would suffice. Light sources having appropriate wavelengths and meeting the other requirements of the device include: gas and diode lasers, light emitting diodes (LEDs), and incandescent lamps.

The width of the wavelength band for broadband sources will need to be limited in order to approximate a monochromatic light source, or the broadband source integrated to account for wavelength dependence.[1] One possible criterion is to limit the ratio of the wavelength band to the average wavelength, with integration used to estimate the resulting errors from assuming a monochromatic light source. The power distribution may be expressed as the percentage of light source power provided over various wavelength bands. Any spectral power spikes present outside of the roughly normal shape should be suppressed in order to avoid errors in the application of Bouguer's law. These criteria are an approximation; a monochromatic light source is preferable.

The costs of lasers, especially diode lasers, continue to drop as they are incorporated in devices with economies of scale. In addition, the wavelength choices for lasers continue to expand. The coherent light from laser devices has a very narrow wavelength band, eliminating the need for the narrowband filters required for other sources. In addition to the benefits of cost and wavelength choice, laser sources are also available in a variety of packages designed for easy incorporation into commercial devices, especially in the medical field. High quality regulated laser power supplies, heat sinks, and modular components are available. Lasers are also available with fiberoptic "pig tails" for delivery of the light. These "pig tails" may have standard fiber optic connectors on the far end or can be provided with optical heads that provide a collimated light beam of a specified size. In the past, stable power supplies and signal conditioning to reduce noise in the measurement signal were costly. It is unclear as to whether the lasers currently made are stable enough to avoid the significant costs associated with stabilization systems.

A wide variety of LEDs are available in visible wavelengths. The major disadvantage of using LEDs is the wavelength range of the devices, frequently on the order of 100 nm. Narrowband filters would be necessary to avoid errors in the extinction coefficient on the order of 10%. LEDs, however, are very inexpensive, available in a wide range of wavelengths and packages, rugged, long lasting, and stable. These devices are available with packages including various lenses, as well as packages specifically made for easy attachment to plastic fiber optic materials. These packages are necessary in order for the light to approximate collimated light. Apertures may also be necessary to tailor the spatial characteristics of the light beam since the relationship between light power over the diameter of the LED is typically a trimodal distribution.

The intensities of incandescent sources have proved noisy but stable in the past compared to laser sources.[4] These light sources are very inexpensive, but in order to meet the requirements of the smoke measurement device they require stable power supplies to keep the filament temperature constant, filters to narrow the wavelength range, and collimating optics. The necessary filters and optics increase the cost and complexity of the devices. The advantage goes to the laser sources, however, if a compensation system is installed, such as a reference detector, which will compensate for sinusoidal fluctuations in the laser signal.

5.2 Optics

In past extinction devices, the laser light source was split producing a reference beam and a measurement beam. The beam splitter was difficult to manufacture, to tune, and to maintain. Small, self contained, low cost fiber optic splitters are now available with connectors on each end. These splitters, used in conjunction with fiber optics for light delivery, could replace the splitters previously used in the extinction device. Narrowband couplers, where the split ratio is dependent on wavelength, and wideband couplers, where the split ratio is independent of wavelength are available for this purpose.

Fiber optics utilizing glass fibers are available that include optical heads attached to either or both ends. The fibers may be combined with adjustable mounting hardware, lens holders, adapters, brackets, and beam splitters for light beam delivery. These components are marketed toward OEM applications, and allow for easy application of fiber optic technology since all of the connections to the fiber are made by the manufacturer. Advantages of these components are easy alignment, stability of the optical fiber, and insensitivity of the fiber system to thermal and mechanical perturbations. The costs of these components, however, is prohibitive in a device of low to moderate cost.

A low cost alternative to glass fibers which are also easier to use are plastic optical fibers. The optimal wavelength (efficiency) for plastic fibers is at approximately 660 nm, which is consistent with use in extinction measurement. At this wavelength, plastic fibers are suitable for use at distances of over 100 m. Plastic fiber optics consist of a fiber core made of PMMA, with a PVC or PE sheath. The total diameter of the fiber is approximately 2.2 mm. These fibers are easier to work with than glass fibers due to their greater thickness, and can be cut using a knife. Originally designed for automotive applications, the fibers are resistant to mechanical shock and can be used at temperatures up to 85 °C. LED emitters and various detectors are available with connectors that are easy to attach to fibers.

Optical lenses and filters may be necessary for some designs incorporating broadband light sources or non-coherent light sources. Neutral density filters may also be used for calibration of the light extinction device. It is useful to note that there is a practical minimum for the quantity of light extinction from a standard glass filter due to surface losses. This lower limit due to reflection with neutral density filters results in a transmittance of 0.92. (8% loss from reflection for Schott glass filters)[26,*] Antireflection coatings can increase the transmittance to approximately 0.99 or more, but their performance is wavelength dependent. (<1% loss from reflection for multilayer coated Melles Griot lenses)[27,*]

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[*]The mention of particular manufacturers's products does not constitute endorsement by NIST, nor does it indicate that the products are necessarily those best suited for the intended purpose.

5.3 Detectors

Photodiodes have advantages that make them the best light detector choice for this application. They include low cost, a high level of reliability and ruggedness, very reproducible sensitivity from device to device, excellent linearity, excellent dynamic range, and a high level of stability. In addition, they have a large dynamic range (pW to mW of optical power). Avalanche photodiodes can be used to increase signal to noise ratio at low powers (pW) since they have internal gains up to about 100 times. A wide variety of doping compounds allow wavelength responses from 190 nm to >2000 nm. For this application, silicon based (190 to 1100 nm) and germanium based (up to 1600 nm) photodiodes are probably most appropriate.

A good second choice for detectors would be phototransistors and photodarlingtons which have the advantage of providing current gains of 100 to 100,000. This gain allows for a high level signal to be provided by the detector, reducing the need for interference and noise to enter the signal path, and reducing the potential for additional signal amplification. They possess many of the advantages of photodiodes, but fall short of photodiodes in linearity, stability, reproducible sensitivity, spectral response (350 nm to 1100 nm), and frequency bandwidth. The limitations applicable to this application are linearity, stability, and reproducible sensitivity. Photodiodes and phototransistors are widely available from many manufacturers, and are produced in many different package configurations. These packages include built-in lenses and are made for easy mating to plastic optical fibers.

Other types of detectors, such as photomultiplier tubes, photoconductive sensors, and optical integrated circuits have one or more significant disadvantages that make them unsuitable for this application. These include high cost, poor sensitivity reproducibility, non-ideal wavelength range, and "long-term memory" where response is a function of the illumination history of the detector.

5.4 Electronics

Amplification of the detector signal is typically necessary in order to provide signals that can be conveniently transmitted some distance to data acquisition systems. Logarithmic amplifiers are particularly suitable since the wide illuminance range of the smoke measurements, which can exceed several decades, will result in a range compatible with data acquisition devices. In addition, amplifiers are available that convert current flows to electric potentials in one package. Of particular interest are logarithmic ratio amplifiers that report the ratio of two signals. One signal would be the attenuated signal, the other a reference signal. The ratio measurement takes into account changes in the incident intensity over time due to power supply or light source instabilities and aging of the light source over time.

In order to reduce noise in optical measurements, previous work indicates that attention should not be focused on stabilizing the light source, but rather on the measured signals. A very low cost feedback noise cancellation circuit is proposed by Hobbs[28], which compares a reference

beam to a signal beam. An automatic electronic subtraction circuit cancels noise identically over a large frequency range. The literature contains schematics for such a device. These devices have been shown to perform better than feedback-to-laser power supply type circuits. An in-depth discussion is also included concerning noise cancellation schemes and the shot noise limit.

6.0 Performance Guidelines for Extinction Instrument

6.1 Degree of Light Extinction Expected

The degree of light extinction expected to be encountered is dependent on many factors including: heat release rate (HRR) of the fire (the design of the extinction device is based on the HRR design limit of the hood system), the entrainment of the fire (arrangement of the smoke collection hood with respect to the base of the fire and the fire height), the smoke producing propensity of the fuel and fuel array (smoke yield), the ventilation conditions of the fire (enclosure), the combustion mode of the fire (unburned pyrolysis, smoldering combustion, flaming combustion, fuel limited, ventilation limited), and the path length of the measuring beam. For purposes of this section, the extinction device is to be designed for an existing exhaust hood in the Large Fire Research Facility at NIST, referred to as the furniture calorimeter. In addition, since the general values for the specific extinction coefficient are to be used for the determination of smoke yield, the fires are assumed to be over ventilated, flaming fires.

The extinction coefficients and I/I_0 values for various fires from previous research are listed in Table 1. These fires represent the range of fire sizes and fuels that are expected in the furniture calorimeter. The extremes in the table for the values of I/I_0 are highlighted. These values are to be used for the design of the light extinction instrument, representing the extremes of light and heavy smoke conditions in the exhaust duct.

6.2 Uncertainty Analysis

In order to determine the accuracy and precision necessary for the extinction device, the uncertainties associated with the other measurements necessary for the calculation of smoke yield were determined, and are listed in Table 2. The standard uncertainties in the table include Type A components where sufficient data was available, as well as Type B measures of uncertainty. The listed uncertainties are based on a coverage factor of 1, corresponding to a 68.27 % confidence interval for a normal probability distribution. For calculation of uncertainties, nominal values were derived to represent expected values for variables in the analysis.

Table 1. Extinction coefficients and values of I/I_0 for various fires.[14]

Fuel	Heat Release Rate, Fuel Array Size	Extinction Coefficient (m^{-1})	I/I_0*
Propane (sand burner)	360 kW, 1000 mm diameter	0.42	0.816
	110 kW, 1000 mm diameter	0.061	0.971
	110 kW, 1000 mm diameter	0.104	0.951
Heptane (pool fire)	60 kW, 310 mm diameter	0.12	0.944
	226 kW, 500 mm diameter	0.251	0.886
Wood Crib (sugar pine)	50 kW	0.125	0.941
	50 kW	0.050	**0.976**
Polyurethane (2 cribs)	300 kW	4.87	0.095
Crude Oil (pool fire)	65 kW, 400 mm diameter	0.90	0.648
	175 kW, 600 mm diameter	2.30	0.330
Polystyrene	500 kW, estimated	7.5	**0.0270**

*Based on 0.48 m path length.

Note: Values of specific extinction coefficients for similar fuels and fire sizes are tabulated in reference [29].

Table 2. Measurement uncertainties for calculation of smoke yield. (Equation 6)

	Nominal Value	u(%)	u
K_{ex}	1.0 m^{-1}	3 (10) [(a)]	0.030 m^{-1}
$\dot{m}(T_1)$	2.7 kg/s	3	0.081 kg/s
K_m	8.5 x 10^3 m^2/kg	12 [(b)]	1.0 x 10^3 m^2/kg
L	0.483 m	2.0	9.7 x 10^{-3} m
$\rho(T_1)$	1.0 kg/m^3	0.80	8.0 x 10^{-3} kg/m^3
$\dot{m}_f$ [(c)]	10. x 10^{-3} kg/s	2.0 [(d)]	2.0 x 10^{-4} kg/s
T_1	350 K	0.80	2.8 K

Notes: (a) Corresponds to uncertainty in the case of low smoke level with I/I_0 of 0.976
(b) 6% for well known fuel composition
(c) Includes estimate for buoyancy induced changes on load cell.
(d) 5% for fast burning rate or slow burning rate.

Possible uncertainties arising from the concentration, temperature, and velocity profiles are not included. Smoke deposited in the stack is also neglected.

In order to determine the levels of uncertainty in the results of a light extinction measurement and the associated calculation of smoke yield, the individual uncertainties listed above were combined using the *law of propagation of uncertainty*.[30] Table 3 lists the results of the calculation.

Table 3. Combined standard uncertainties for smoke yield.

Smoke level	u_ϵ	u_ϵ/ϵ	Notes
High	4.10×10^{-3}	0.13	
Low	5.15×10^{-3}	0.16	
Low	5.98×10^{-3}	0.19	$u(\dot{m}_f)$=10%
Low	5.98×10^{-3}	0.19	$u[\dot{m}(T_1)]$=10%
High	5.10×10^{-3}	0.16	$u(K_{ex})$=10%
High	2.44×10^{-3}	0.077	$u(K_s)$=6%
Low	3.96×10^{-3}	0.12	$u(K_s)$=6%
Low	not available	≈0.15	Old NIST system.

6.3 Extinction Instrument Performance Requirements

In order to make useful measurements, the stability of the extinction device over time must be adequate for values of I/I_0 that may be experienced. The values of I/I_0, including uncertainty and drift, shall be within the following ranges for 20 minutes of operation:

1. With no smoke present in the sample area the reported value of I/I_0 shall be between 0.9976 and 1.0024. This criteria is necessary for accurate and precise measurements of low smoke concentrations.

2. To simulate dense smokes, the readings shall be made with a 2.5% transmittance neutral density filter installed. The reported value of I/I_0 shall be between 0.0224 and 0.0279.

These values correspond to the 10% and 3% uncertainties listed previously for the value of K_{ex} in conditions of high smoke and low smoke respectively. The limits represent uncertainties with a coverage factor of 1, relating to a 68.27% confidence interval.

6.4 Design Characteristics

The following list contains design characteristics for the light extinction measuring device that are consistent with the goals previously stated for the use of the device for determination of

smoke yield in the furniture calorimeter at NIST:

1. The light source should be a collimated, single wavelength source, with a wavelength near the center of the visible spectrum. Collimated light sources simplify the design of the device, reducing the optics necessary. The single wavelength is consistent with Bouguer's law. A wavelength near the center of the visible spectrum allows for easier alignment of the device and is more likely to correlate with white light measurements. If a broadband light source is used, the wavelength band must be limited with a filter or the source integrated to account for wavelength dependence and provide agreement with Bouguer's law.[1] The power distribution may be expressed as the percentage of light source power provided over various wavelength bands.

In addition, there should be no spikes in the power output response of the light source at wavelengths distant from the median. These spikes would result in non-conformance with Bouguer's law.

2. The detector should be a silicon photodiode. Photodiodes have operational characteristics consistent with the use of the device, are of low cost, are linear over more than six decades of light intensity, and are available in a variety configurations.

3. The design should incorporate a purge air system to prevent sooting of the optics. The effect of the purge air on the path length must be determined.

4. Reduction of forward scatter. The schematic design shown in Figure 2 is recommended for the reduction of forward scatter. The recommended acceptance angle is 2 degrees or less.

5. Path length. The path length should be approximately 0.483 m (19 inches) for single pass devices for consistency with the existing duct in the facility, as well as to provide adequate extinction for measurement.

6. Noise reduction. The device should incorporate a reference detector and comparitor circuit to compensate for drift in the output of the light source. The feedback noise cancellation circuit proposed by Hobbs and discussed in section 5.4 should be considered.

7. Fiber optic reference detector splitter. A plastic fiber optic splitter for the reference detector would alleviate the manufacture and alignment difficulties associated with the common optical splitters used in the ASTM E 1354 - 92 device.

8. Output signals from the device should be compatible with common data acquisition devices, ie. provide a signal of 4 mA to 20 mA or 0 V to 10 V over the measurement range. Voltage output is preferable.

9. Vibration resistance. The output of the device should be stable under vibrations present in the ducts during fire tests.

10. Alignment. The device should be able to be aligned without disassembly or removal from the duct. Alignment should be maintained over the operating temperature range of the duct.

11. Maintenance interval. The device should be capable of operation for a period of one year without maintenance.

12. Cost. The cost of the device should not exceed $10,000.

13. Calibration. The device should be capable of being calibrated with neutral density filters without disassembly or removal.

7.0 Conclusions

Light extinction measurements in smoke produced by fires are commonly conducted in both fire experiments and standard fire tests. The measurement of extinction in the past has been accomplished using a wide variety of extinction measurement device designs, many of which do not take into account previously determined sources of uncertainty. This paper has investigated the conduct and use of smoke extinction measurements in the past, and has discussed the characteristics of smoke and its interaction with light that affect these measurements. For purposes of this paper, extinction measurements will be used in conjunction with parallel smoke research to allow for the calculation of smoke yield using measurements of light extinction and without extensive knowledge of the fuel makeup. These calculations are valid for over-ventilated, flaming fires which produce a high percentage of smoke in the form of carbonaceous particulate. Pyrolysis smoke, and the smoke from under-ventilated fires will require measurement of the specific extinction coefficient before using this methodology.

The characteristics of a suitable light extinction device were discussed, and include: a sound technical design, incorporation of modern components, good accuracy and precision, the ability to operate in dirty environments with little maintenance, and availability at moderate cost. Commercial products designed to measure light extinction in stacks for pollution monitoring may be appropriate for measuring light extinction in the instrumented exhaust hoods of the NIST Large Fire Research Facility, and similar fire research facilities.

This paper proposes the use of smoke extinction devices with similar characteristics so that results from various laboratories can be compared easily. In addition, it is proposed that the designs for smoke extinction meters be referenced, as well as levels of uncertainty published with results.

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Appendix A - Manufacturers of Extinction Measurement Devices*

Datatest
6850 Hibbs Lane
Levittown, PA 19057
(215) 943-0668
Notes: Of particular interest are models 109 and 90A

Durag
6175 Cahill Ave.
Inver Grove Heights, MN 55076
http://www.durag.com
(612) 451-1710

Monitor Labs, Inc.
76 Inverness Dr. East
Englewood, CO 80112
http://www.monitorlabs.com
(800) 422-1499

Rosemount Analytical
attn: Doug Gardner
http://www.eta-is-opacity.com
(813) 784-2600

SICK Optic-Electronic, Inc.
7694 Golden Triangle Dr.
Eden Prairie, MN 55344
(612) 941-6780

United Scientific Inc.
5310 N. Pioneer Rd.
Gibsonia, PA 15044
(412) 443-8610
Notes: Of particular interest is model 500.

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*The mention of particular manufacturers's products does not constitute endorsement by NIST, nor does it indicate that the products are necessarily those best suited for the intended purpose.

Appendix B - Component Manufacturers*

Light Sources

Laser/Fiber Optic Combinations

Point Source Ltd
Leylands Park
Winchester, Hampshire
S021 1TH England
+44 (0)1703 601470
Email: sales@pointsource.co.uk
http://www.point-source.com
Notes: Lasers mated to optical fibers, optical fibers mated to collimating optics.

Melles Griot
Electro-Optics, Instruments
4601 Nautilus Court South
Boulder, CO 80301
(800) 326-4363
http://www.mellesgriot.com
Notes: Diode lasers mated to optical fibers.

Light Emitting Diodes (LEDs)

EG&G VACTEC Optoelectronics
10900 Page Blvd.
St. Louis, MO 63132
(314) 423-4900
http://www.egginc.com/optogrp

Siemens Components, Inc.
10950 North Tantau Ave.
Cupertino, CA 95014
http://www.sci.siemens.com
Notes: LEDs, LEDs with couplings for attachment of optical fibers.

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*The mention of particular manufacturers's products does not constitute endorsement by NIST, nor does it indicate that the products are necessarily those best suited for the intended purpose.

Silonex, Inc.
2105 Ward St.
Montreal, Quebec
H4M 1T7 Canada
(514)744-5507
http://www.silonex.com
Notes: Local Distributer: Nelson Electronics, Inc.
3992 Old Columbia Pike
Ellicott City, MD 21043
(410) 465-1946

Optics

Fiber Optic Splitters

NetOptics
Sunnyvale, CA
(408)737-7777
http://www.netoptics.com
Notes: Various split ratios and connector types available. Wavelength independent splitters available; important due to wavelength differences between typical fiber optic applications and that of the extinction device.

Mounting Hardware

Point Source Ltd
Leylands Park
Winchester, Hampshire
S021 1TH England
+44 (0)1703 601470
Email: sales@pointsource.co.uk
http://www.point-source.com
Notes: Mounting hardware and devices allowing for adjustment and alignment of lasers and other optical components. Hardware is designed for OEM applications.

Optima Precision, Inc.
775 SW Long Farm Rd.
West Linn, OR 97068
(503) 638-2525
http://optima-prec.com
Notes: Laser diode mounting systems incorporating apertures and lenses.

Plastic Optical Fibers

Siemens Components, Inc.
10950 North Tantau Ave.
Cupertino, CA 95014
http://www.sci.siemens.com

Detectors

EG&G VACTEC Optoelectronics
10900 Page Blvd.
St. Louis, MO 63132
(314) 423-4900
http://www.egginc.com/optogrp
Notes: Photodiodes, photodiode/amplifier packages, phototransistors, photodarlingtons, photoconductive cells, photo integrated circuits (ICs).

Hamamatsu Corp.
360 Foothill Rd.
P.O. Box 6910
Bridgewater, NJ 08807
(908)231-0960
Notes: Photodiodes, phototransistors, photoconductive cells, photo integrated circuits (ICs).

New Focus, Inc.
2630 Walsh Ave.
Santa Clara, CA 95051
(408)980-8088
http://www.newfocus.com
Notes: "Nirvana" auto-balanced photoreceivers. Incorporates auto-balancing noise cancellation circuit methodology developed by Hobbs.

Siemens Components, Inc.
10950 North Tantau Ave.
Cupertino, CA 95014
http://www.sci.siemens.com
Notes: Detectors with couplings for attachment of optical fibers. Photovoltaics, photodiodes, photodiode/amplifier packages, phototransistors.

Silonex, Inc.
2105 Ward St.
Montreal, Quebec
H4M 1T7 Canada
(514)744-5507
http://www.silonex.com
Notes: Photodiodes, phototransistors, photodarlingtons, photo ICs.

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Local Distributer:	Nelson Electronics, Inc. 3992 Old Columbia Pike Ellicott City, MD 21043 (410) 465-1946

Electronics

Analog Devices, Inc.
One Technology Way
P.O. Box 9106
Norwood, MA 02062
(781) 329-4700
http://www.analog.com

BURR-BROWN
P.O. Box 11400
Tucson, AZ 85734
(520)746-1111
http://www.burr-brown.com
Notes: Of particular interest is the model LOG100 logarithmic ratio amplifier.

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The light attenuation characteristics of the smoke produced by fire are commonly measured in both fire experiments and standard fire tests. The results of these measurements are traditionally used for building and fire code regulatory purposes, design and testing of fire detectors, advanced material development, and life safety calculations. In addition, recent research suggests that for various fuels burning in over-ventilated fires, light extinction measurements may be used for the determination of the mass concentration of smoke per unit volume and smoke yield. The methods used for measuring light extinction in various fire tests and experiments are not consistent, however, and frequently do not take into account previously determined sources of uncertainty. This paper discusses existing methods of light extinction measurement, theoretical aspects of light extinction, and measurement device features that are necessary of the accurate and precise measurement of extinction. The topics are discussed in the context of smoke mass concentration and smoke yield determination for fire experiments conducted in the furniture calorimeter at the NIST Large Fire Research Facility and in other similar fire research facilities

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

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